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Managing Invasive Species in the Presence of Endogenous Technological Change with Uncertainty

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This research incorporates the development and adoption of an induced technology under uncertainty into a conceptual dynamic model to more broadly examine efficient policies for mitigating invasive species infestations. We find that under optimal policy, marginal costs of adopting conventional control measures are equal to the sum of the marginal benefits from development and adoption of new technology, as well as the use of conventional control measures. This result implies that a resource allocation designed for controlling invasive species is not adequate when an induced technology is not considered. Our results also reveal that the shadow values associated with the probabilities of developing and then adopting an induced technology increase as the shadow values associated with the stock of an invasive species population increase.

KEY WORDS: Adoption; biological pest control measures; chemical/mechanical control measures; comparative dynamic analysis; induced technology; invasive species

1. INTRODUCTION

Given the complexity and the magnitude of potential economic and ecological damages from an invasive species infestation, results from bioeconomic models have become increasingly relevant to economic and policy discussions.[(1–8)] However, despite growing evidence that government policies and market conditions influence the direction of technological change, to our knowledge, technological innovation has not been examined as a means of managing invasive species. Technical change is largely driven by the private sector and induced in response to government policies and market conditions. Ciba Seeds (now Novartis Seeds) and Mycogen Seeds, for example, introduced the first Bt corn (*Bacillus thuringiensis*) hybrids in 1996 to protect corn production from the European corn borer, which caused crop damage and control costs exceeding $1 billion each year.[(9)]

Whether or not economic and ecological damages from an invasive species can be manageable largely depends upon the technologies available for controlling the invasive species. Technical change could thus respond to economic and policy incentives for invasive species management.[(10,11)] While endogenous technological change is classified into the two broad and disjoint categories of invention and learning-by-doing,[(12–14)] the more specific category of technological change we focus on is the outcome of deliberate research by joint efforts of government, academic, and corporate enterprises, aimed at the development of an endogenously induced technology associated with the use of a factor of production.[3] Following Grubb, Kőhler, and Anderson,[(10)]

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[3]Examples of induced technology include such innovations as genetically engineered seeds currently available for corn, soybean, cotton, and other crops. Another current example includes that

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for this study we define induced technological change with respect to invasive species mitigation as the component of technical change influenced over time by the costs of managing and controlling the invasive species to farmers. Even after an induced technology is developed, the adoption of this new technology may be delayed if the net economic benefits resulting from the adoption of this technology are less than those from the adoption of conventional control measures.[4]

Within the dynamic framework of invasive species management, we endogenize potential technical innovations such as the development of genetically engineered seeds that both reduce management costs and mitigate invasive species impacts. Induced technology enters our modeling framework with respect to the timing of introducing a new technology that contributes to mitigation of species impacts and the timing of adopting the new technology. Following Kiefer,[(15)] we assume that the probabilities of developing and adopting technical innovation occurring at any time, given that the development and adoption of technical innovation have not occurred yet, are increasing functions of the cost to farmers of managing/controlling the invasive species, as well as the innovation investment itself.[5] Thus, new technologies emerge in response to the costs of managing the invasive species associated with the use of a factor of production. Recognizing the potential farm-level damages from an invasive species, firms (and government) are assumed to respond to these costs as an indication of farmers' (society's) willingness to pay to avoid damages associated with the invasive species.

The relevant literature for this research area includes the work by Goeschl and Perino,[(16)] who generalized the modeling formulation for the optimal pollution path and the optimal timing of R&D when addressing pollution/management issues. Goeschl and Perino[(16)] considered never-perfect backstop technologies developed and adopted to provide a solution to an existing pollution problem, while for our study, we consider an induced perfect substitute technology, for convenience, which mitigates the costs of adopting conventional control measures for managing the invasive species (see footnote 1 for examples).

The remainder of our article is organized as follows. First, we present a bioeconomic dynamic model for determining the optimal allocation of management resources between alternative control activities for managing an invasive species in the presence of an induced technology with uncertain dates of innovation and adoption. Economic properties of the optimal solutions for managing the invasive species with these uncertainties are discussed. Second, we conduct a series of comparative dynamic analyses to evaluate how invasive species' characteristic variables affect the optimal policies for the invasive species' management in the presence of new technology development and its adoption with uncertainty. We conclude by discussing how an induced technology influences invasive species policy-management parameters.

2. THE MODEL

An invasive-species biological population tends to grow at a rate that follows a logistic growth function. For the case where a fraction of the stock of an invasive species is removed by use of the conventional control measures, the rate of change of the invasive species stock is then represented as follows:[(17)]

$$\begin{aligned}\frac{\partial z(t)}{\partial t} &= g(Q(t))z(t)\left[1-\frac{z(t)}{V}\right]\\ &\quad - g(Q(t))[k(E(t))z(t)]\\ &\quad \times\left[1-\frac{k(E(t))z(t)}{V}\right],\\ &= g(Q(t))[1-k(E(t))]z(t)\\ &\quad \times\left[1-\frac{(1+k(E(t)))z(t)}{V}\right], \qquad (1)\end{aligned}$$

where $z(t)$ is the stock of an invasive species in year t and $z(t=0)=z_0$, $g(Q(t))$ is the rate of intrinsic growth of the invasive species, Q represents the level of biological pest control measures implemented, and V represents the maximum possible population of the invasive species that depends on the maximum resources available for infestation. The

in 2004, scientists from USDA's Agricultural Research Service and the University of Illinois collaborated on the discovery of a single gene, tentatively named *Rag*1, which confers resistance to soybean aphids (*Aphis glycines Matsumura*). This development has set the stage for seed companies to breed existing high-yielding but susceptible cultivars that should withstand the soybean aphid without help from insecticides.[(20)]

[4]Examples of the induced technology adoption process are included in articles by Alexander and Mellor,[(21)] Hyde *et al.*,[(22)] and Hubbell *et al.*[(23)]

[5]Hazard function methods have been employed within economic studies where the duration of activities matter, such as the time of adoption for new technologies[(24)] and time of entry for new firms.[(25)]

parameter $k(E(t))$ is a fractional coefficient ($0 \leq k \leq 1$) representing the removal rate of the invasive species population stock, where $E(t)$ is assumed to represent the level of chemical and/or mechanical control measures implemented, and where $\frac{\partial k}{\partial E} > 0$. Biological pest control measures are defined as those that reduce the ability of the species to multiply, such that ($\frac{\partial g}{\partial Q} < 0$),[6] including, for example, such measures as the sterilization of males to control sea lamprey populations in the Great Lakes,[(18)] and/or introduction of the seed wasp (*Megastigmus transvaalensis*) to control the Brazilian Peppertree in Florida.[(19)]

Next, we consider the case of a new technology that mitigates the costs of adopting biological measures and chemical/mechanical control measures for managing the invasive species. To endogenize the timing of developing a new technical innovation in the future we employ a hazard function approach where the probability of developing a new technical innovation occurring is influenced by the costs of adopting the biological and/or chemical/mechanical control measures for managing the invasive species. That is, the extent to which technical innovation is an increasing function of the cost of invasive species management depends on farmers', as well as society's, desire to combat the increasing species management costs. In the absence of a technical innovation, invasive species management and control costs to farmers and damages resulting from an invasive species infestation to society are presumed to increase.

The probability of developing a technical innovation occurring at any time t, given that an innovative technology has not been developed yet, is modeled as an increasing function of the cost of adopting control measures for managing the invasive species. First, we let $M(t)$ be the probability associated with the development of a technical innovation occurring by time t where $M(t = 0) = 0$. Then, we can specify the conditional probability of developing a technical innovation at time t, $h(E(t), Q(t))$, as the probability that the development of such an innovation will occur during the next time period, $t + \Delta t$, given that a new technology has not been developed at time t.

We assume that the time to develop innovation is uncertain, but that the likelihood of developing a new technology, which would be developed to avoid higher costs associated with invasive species management, is expressed as follows:[7]

$$h[E(t), Q(t)] = \left(\frac{\partial M(t)/\partial t}{1 - M(t)}\right), \quad \text{where} \quad h[E(t=0), Q(t=0)] = 0, \ \frac{\partial h}{\partial E} > 0, \ \frac{\partial h}{\partial Q} > 0, \tag{2}$$

and $\frac{\partial M(t)}{\partial t}$ is the probability density function for innovative technology development. Equation (2) can be rewritten as a state equation as follows:

$$\frac{\partial M(t)}{\partial t} = h[E(t), Q(t)][1 - M(t)], \quad \text{where} \quad M(t) = 1 - e^{-h[E(t), Q(t)]t}. \tag{3}$$

Once a technical innovation occurs at time t^*, economic benefits associated with the management of an invasive species depend largely on whether the innovative technology is adopted. Therefore, we let $N(\tau)$ be the probability of the adoption of a technical innovation developed at time $\tau \geq t^*$, where $N(\tau = t^*) = 0$. The conditional probability of adopting a new technology at time τ, $m(E(\tau), Q(\tau))$, is the probability that adoption of such an innovation will occur during the next time period, $\tau + \Delta\tau$, given that a new technology has not been adopted at time τ. We also assume that the adoption time of innovation is uncertain, but that the likelihood of adopting a new technology to avoid higher costs associated with invasive species management is expressed as follows:

$$m[E(\tau), Q(\tau)] = \left(\frac{\partial N(\tau)/\partial \tau}{1 - N(\tau)}\right), \quad \text{where} \quad \tau \geq t^*, \ m[E(\tau = t^*), \ Q(\tau = t^*)] = 0, \tag{4}$$

$\frac{\partial m}{\partial E} > 0$, $\frac{\partial m}{\partial Q} > 0$, and $\frac{\partial N(\tau)}{\partial \tau}$ is the probability density function. Equation (4) can be rewritten as a state equation for innovative technology adoption as follows:

$$\frac{\partial N(\tau)}{\partial \tau} = m[E(\tau), Q(\tau)][1 - N(\tau)], \quad \text{where} \quad N(\tau) = 1 - e^{-m[E(\tau), Q(\tau)]\tau}. \tag{5}$$

[6] Considering the past experience of costly failure, one could assume that $\frac{\partial g}{\partial Q}$ is close to zero.

[7] Application of a hazard function approach while considering the uncertainty of innovation timing derived from research investments was suggested by Kiefer,[(15)] and the uncertain discovery time of an invasive species was considered by Kim *et al.*[(3)]

Subsequently, the related dynamic optimization problem involves maximizing the net social economic benefits for invasive species management in the presence of technological change under uncertainty, such that:[8]

$$\begin{aligned}\text{Max } W &= \int_0^T e^{-rt}\{(1 - M(t))[NB(Y(x, z(t)))\\ &\quad - C_b(E(t), Q(t))]\\ &\quad + M(t)[N(t)(NB(Y(w)) - C_a(R))\\ &\quad + (1 - N(t))(NB(Y(x, z(t)))\\ &\quad - C_b(E(t), Q(t)))]\}\delta t\\ &= \int_0^T e^{-rt}\{[NB(Y(x, z(t)))\\ &\quad - C_b(E(t), Q(t))]\\ &\quad + M(t)N(t)[(NB(Y(w)) - C_a(R))\\ &\quad - (NB(Y(x, z(t)))\\ &\quad - C_b(E(t), Q(t)))]\}\delta t, \end{aligned} \tag{6}$$

subject to the state Equations (1), (3), and (5), as well as $N(T) = N_T$, where T is the terminal time period,[9] N_T is a known constant, r is the rate of discount, Y is output, NB represents net economic benefits of output (excluding the costs of managing the invasive species) in terms of consumer and producer surpluses, x and w identify conventional and induced technologies, respectively, $C_b(E(t),Q(t))$ represents the costs to farmers of managing the invasive species with the implementation of chemical/mechanical and biological pest control measures before the adoption of a new technology, and $C_a(R)$ represents the investment costs for developing an innovative technology. The net economic benefits resulting from the adoption of an induced technical innovation occurring, $NB(Y(w))$, are increasing over time as a function of the discounting of these costs.[10] Therefore, the adoption of an induced technology requires that their net economic benefits, $[NB(Y(w)) - C_a(R)]$,[11] be greater than or equal to the net economic benefits (less invasive species management costs) associated with the conventional technology at any given year, $[NB(Y(x, z(t))) - C_b(E(t),Q(t))]$. Equation (6) assumes that an induced technology (i.e., w) is developed with the probability of $M(t)$, and that this new technology would be adopted with the probability of $N(t)$, while the rest, $(1\text{-}N(t))$, would use the conventional technology.

The Hamiltonian equation associated with Equations (1), (3), (5), and (6) (where the arguments of the variables E and Q, for convenience, are hereafter omitted) is:

$$\begin{aligned}H = e^{-rt}\Big\{&(NB(Y(x, z(t)))\\ &- C_b(E(t), Q(t))) + M(t)N(t)[(NB(Y(w))\\ &- C_a(R)) - (NB(Y(x, z(t))) - C_b(E(t), Q(t)))]\Big\},\\ &+ \lambda_1(t)h(E, Q)[1 - M(t)] + \lambda_2(t)m(E, Q)[1 - N(t)]\\ &+ \lambda_3(t)g(Q)(1 - k(E))z(t)\left[1 - \frac{(1 + k(E))z(t)}{V}\right],\end{aligned} \tag{7}$$

where E and Q are control variables, M, N, and z are state variables, and λ_1, λ_2, and λ_3 are adjoint variables. The necessary conditions for optimality are represented in Appendix A.[12]

The economic interpretation of optimal conditions presented in Equations (A.1) through (A.8) is better served by first understanding the adjoint variables λ_1, λ_2, and λ_3. Solving the differential equations in Equations (A.3) through (A.5), the adjoint variables λ_1, λ_2, and λ_3 are represented in Equations (B.1) through (B.3), respectively (Appendix B). But, before interpreting these conditions, it is important to recognize that when an induced technology

[8] A reviewer correctly pointed out that we assume no risks and costs associated with the release of genetically modified organisms.

[9] We are indebted to a reviewer for the comment that the time frame for induced technology development likely involves a much shorter time scale than infinity.

[10] Long-term costs to farmers who choose to adopt a seed-based induced technology by continually paying the rights to use the seed and forfeit rights to produce their own seed are incorporated into the net economic benefits associated with the adoption of the induced technology, $NB(Y(w))$.

[11] For simplicity, investment costs for developing an innovative technology represent amortized values.

[12] The optimal solutions satisfying the necessary conditions presented in Equations (A.1) through (A.9) must also satisfy sufficient conditions. Sufficient conditions derived by Mangasarian[(26)] (and later by Takayama[(27)]) require strict concavity of the Hamiltonian function with respect to the state and control variables, which is considered to be rather strong and their theorems do not apply to many economic problems.[(28)] Even though Seierstad and Sydsaeter[(28)] also provided sufficient conditions, where the adjoint variables are allowed to be discontinuous at a finite number of time periods, their conditions are also difficult to apply.[(29)] Therefore, we assume a weaker version of sufficient conditions to assure optimality.[(30)]

is developed, its marginal net economic benefits could initially be negative, and then subsequently become positive. However, the eventual adoption of an innovative technology requires that the net economic benefits resulting from the adoption of a new technology, $[NB(Y(w)) - C_a(R)]$, must be greater than those from the use of the conventional technology, $[NB(Y(x,z)) - C_b(E,Q)]$. Therefore, the adjoint variable λ_2 in Equation (B.2), which measures the marginal contribution of the state variable N to the objective function value (i.e., the change in the net social economic benefits associated with an increase in the probability of adopting a new technology), is positive, which requires that the adjoint variable λ_1 in Equation (B.1), which measures the marginal contribution of the state variable M to the objective function value (i.e., the change in the net social economic benefits associated with an increase in the probability of developing a new technology), becomes positive some short period after development, but prior to adoption.

Similarly, the adjoint variable λ_3 measures the marginal contribution of the value of the state variable z (the change in the invasive species stock) to the objective function value. Essentially, an increase in the invasive species population would reduce the net economic benefits of species management as a result of greater damages from the larger infestation, but it also leads to an increase in the probability of a new induced technology being developed and adopted because of the increasing costs of managing the invasive species.

Now that we can interpret the adjoint variables, we can explain the economic properties of the necessary conditions for optimality presented in Equations (A.1) through (A.8) in Appendix A. Equation (A.1) states that at in an optimal solution the expected marginal costs (MC) of controlling invasive species with chemical/mechanical control measures equals the sum of the economic benefits (shadow values) resulting from the development and adoption of an induced technology, which will occur because of increased costs of adopting chemical/mechanical control measures, and the value of the reduction of the invasive species stock associated with adoption of chemical/mechanical control measures. Similarly, Equation (A.2) states that at an optimal solution the expected MC of controlling invasive species with biological pest control measures equals the sum of the economic benefits (shadow values) from the development and adoption of an induced production technology, and the value of the reduction of the invasive species stock associated with reducing the intrinsic growth rate of the invasive species infestation.

These optimality conditions differ somewhat from the optimal conditions required in conventional optimal control models of invasive species management designed without considering induced technology. In the case without induced new technologies, the optimal allocation of management resources between alternative control activities requires that the MC of implementing control measures equals the marginal benefits (MB) from the reduction of an invasive species population.[3] When an induced technology is available, however, as shown with Equations (A.1) and (A.2), optimality conditions require that the MC of controlling an invasive species under a conventional technology must equal the sum of the MB resulting from the adoption of an induced technology and those resulting from the adoption of a conventional technology.[13] This result can be explained using Fig. 1, where MC and MC′ represent the MC of managing invasive species before and after, respectively, the adoption of an induced technology. The optimal net social economic benefits for invasive species management, without considering an induced technology, are attained at Z_{CT}, where the MB equals the MC of managing the invasive species with a conventional technology. When an induced technology development and its adoption is considered in a dynamic model for controlling an invasive species infestation, the optimal net social economic benefits are attained at the invasive species stock level Z_{IT}, where the MC of managing the invasive species with a conventional technology less the MB resulting from the adoption of an induced technology equal the MB resulting from the reduction of the invasive species associated with the adoption of conventional technology, as shown in Equations (A.1) and (A.2). This result implies that when the adoption of an induced technology development is not considered in the specification of a dynamic model for mitigating an invasive species infestation, a recommended management resource allocation resulting from that model would be too low. However, even

[13]The optimal conditions as shown in Equations (A.1) and (A.2) are similar to analyses of the benefits of adopting genetically engineered crops in static analyses. For instance, Hyde *et al.*[22] and McBride and El-Osta[31] analyzed the economics of adopting *Bacillus thuringiensis* (Bt) corn to protect against a European corn borer (ECB) infestation by comparing the net revenues from planting Bt corn versus planting conventional corn, including the cost and efficacy of scouting and applying insecticides.

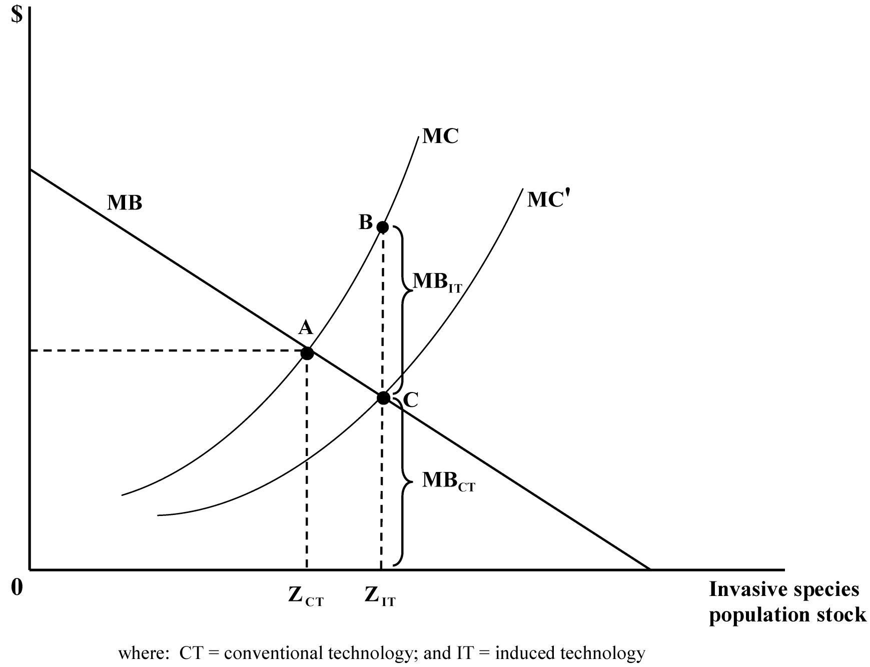

Fig. 1. Welfare effects of an induced technology.

if farmers know that a cost-saving technology is on the way, a recommended management resource allocation resulting from the model without an induced technology would at least be an efficient solution for managing the invasive species, until the lower-cost technology becomes available.[14]

The adjoint Equations (A.3) and (A.4) demonstrate that both the development of a new technology itself and the adoption of this new technology create the values associated with user costs (shadow values). Similarly, Equation (A.5) explains that a reduction in the stock of an invasive species also creates the shadow value. Equations (A.6) through (A.8) are the equations of motion, while Equation (A.9) is the conventional transversality condition, which must hold in the limit as time approaches the terminal time, T.

3. COMPARATIVE DYNAMIC ANALYSES

To gain insight into the properties of optimal decision rules for managing an invasive species in the presence of an induced technology under uncertainty, it is necessary to provide some comparative dynamic analyses concerning the effects of exogenous changes in the characteristics of an invasive species infestation. Therefore, we conduct a comparative dynamic analysis of expected changes in the shadow values, λ_1 and λ_2, associated with the development and adoption of an induced technology, respectively, and the shadow value, λ_3, associated with a reduction in the stock of the invasive species by adopting chemical/mechanical measures and/or biological measures, relative to key characteristics of the invasive species environment. Specifically, we evaluate the comparative dynamic effects of changes in the rate of intrinsic growth (g) and the maximum species population (V), as well as other policy-relevant measures, including the rate (k) at which control measures reduce the invasive species stock.[15] This rate, k, can then be interpreted as an indicator of the level of the budgetary resources necessary to manage the invasive species.

First, inserting $M(t)$ and $N(t)$ from Equations (3) and (5) into Equations (A.1) and (A.2) in Appendix A, respectively, and then taking the total differentiation of the resulting equations and Equation (B.3) in Appendix B leads to the relationships between the adjoint variables and the characteristics of the invasive species infestation (as shown in Appendix C).

[14]The economically efficient allocation of resources for new technology development relative to old technology invasive species management can be evaluated by comparing the co-state variables λ_1, λ_2, and λ_3 (see Kim *et al.*[3]). However, these are beyond the scope of our research. We are indebted to a reviewer for expanding upon this point.

[15]The removal rate of the invasive species stock by chemical/mechanical control measures, k, is treated as a parameter.

(All elements of the matrix in Equation (C.1) are also defined in Appendix C.)

Comparative dynamic results follow from the elements of Equation (C.1), where each has an unambiguous sign as follows:

$$\frac{\partial \lambda_1}{\partial g} > 0; \tag{8a}$$

$$\frac{\partial \lambda_2}{\partial g} > 0; \tag{8b}$$

$$\frac{\partial \lambda_3}{\partial g} < 0; \tag{8c}$$

$$\frac{\partial \lambda_1}{\partial k} < 0; \tag{9a}$$

$$\frac{\partial \lambda_2}{\partial k} < 0; \tag{9b}$$

$$\frac{\partial \lambda_3}{\partial k} > 0; \tag{9c}$$

$$\frac{\partial \lambda_1}{\partial V} < 0; \tag{10a}$$

$$\frac{\partial \lambda_2}{\partial V} < 0; \tag{10b}$$

$$\frac{\partial \lambda_3}{\partial V} > 0. \tag{10c}$$

Equations (8a) through (8c) describe the marginal effects of changes in the rate of intrinsic growth of the species infestation on the shadow values associated with the development and then the adoption of an induced technology, as well as the shadow value of controlling the invasive species population with biological pest control measures. Since the MC of implementing biological pest control measures increases as more biological pest control measures are adopted to reduce the invasive species population stock, the shadow value of reducing the invasive species population stock increases (becomes more negative), as shown in Equation (8c), and therefore, the shadow value of developing and then adopting an induced new technology increases as shown in Equations (8a) and (8b). That is, as the rate of intrinsic growth increases, the need for developing and adopting an induced technology also increases.

Similarly, Equations (9a) through (9c) describe the marginal effects of changes in the removal rate of the invasive species population on the shadow values associated with the development and adoption of an induced technology, as well as the shadow value of controlling the invasive species population stock with chemical/mechanical control measures. Equation (9c) explains that the shadow value of controlling the invasive species with chemical/mechanical control measures declines (become less negative) as the removal rate of the invasive species population stock increases. Therefore, the shadow values associated with both the development and adoption of an induced technology also decline as the removal rate of the invasive species population stock increases, as shown in Equations (9a) and (9b). That is, as the removal rate of the invasive species population stock with mechanical/chemical measures increases, the need for developing and adopting an induced technology declines.

Equations (10a) through (10c) describe the marginal effects of changes in the maximum possible population of the invasive species stock on the shadow values associated with the development and adoption of an induced technology, as well as the shadow value of the population of the invasive species stock itself. The maximum possible population of the stock of the invasive species can be represented by the maximum resources available for a species infestation. For example, in Kim *et al.*,[17] V is defined as the maximum acreage of the Florida Public Conservation Lands subjected to potential infestation with invasive plants. Equations (10a) and (10b) explain that the shadow value of developing and then adopting an induced technology declines as the maximum resources available for species infestation increase. Similarly, the shadow value of controlling the invasive species stock with conventional technology also declines (become less negative) as the maximum resources available for infestation increase. These results simply explain that increases in the supply of resources available for species infestation reduce its shadow price, a straightforward relationship between quantity and price.

4. CONCLUSIONS

This research extends previous work addressing the economics of invasive species management by incorporating an induced technology with uncertainty as a function of the costs of controlling an invasive species population. In conventional invasive species management studies, the optimal allocation of management resources between alternative control activities for managing an invasive species requires that the MB from the reduction of an invasive species population equal the MC of control measures. However, in the case of an induced technology with uncertain development and adoption times, we find that at optimum conditions, an efficient management resource allocation requires that the expected MC of adopting conventional control measures less the MB (shadow values) resulting from the development and adoption of an induced technology (which will occur because of increased costs of adopting conventional control measures) equal the MB resulting from the reduction of the invasive species population stock associated with adopting conventional control measures. This result implies that when a dynamic model for mitigating invasive species infestation is misspecified by not considering an induced technology development, a recommended management resource allocation resulting from that model would be too low.

This study also derives the comparative dynamic results required to assess qualitatively the effect of invasive species characteristic parameters on: (1) the shadow values associated with the probability of developing a new technology; (2) the shadow values associated with the probability of adopting this new technology to mitigate against an invasive species; and (3) the shadow values associated with the invasive species population itself. Our results reveal that the changes in the shadow values associated with the probabilities of developing and then adopting an induced technology are consistent with the changes in the shadow values associated with the adoption of conventional technologies for controlling invasive species.

From a policy perspective, our results demonstrate that when induced technology under uncertainty and a logistic net growth model of invasive species are accounted for, the management resource allocation issue designed for controlling an invasive species is more complex than conventional optimality conditions would imply. Applying conventional optimality conditions could result in less management resources allocated to conventional control measures, while not allowing management resource-allocation decisions to reflect the potential resource savings from induced development of an improved technology.

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APPENDIX A—NECESSARY CONDITIONS FOR OPTIMALITY

$$\frac{\partial H}{\partial E} = 0 \text{ implies}$$

$$e^{-rt}(1 - MN)\left(\frac{\partial C^b}{\partial E}\right) = \lambda_1(1 - M)\left(\frac{\partial h}{\partial E}\right) + \lambda_2(1 - N)\left(\frac{\partial m}{\partial E}\right) - \lambda_3 gz\left[1 - \frac{2kz}{V}\right]\left(\frac{\partial k}{\partial E}\right). \tag{A.1}$$

$$\frac{\partial H}{\partial Q} = 0 \text{ implies}$$

$$e^{-rt}(1 - MN)\left(\frac{\partial C_b}{\partial Q}\right) = \lambda_1(1 - M)\left(\frac{\partial h}{\partial Q}\right) + \lambda_2(1 - N)\left(\frac{\partial m}{\partial Q}\right) + \lambda_3[(1 - k)z]\left[1 - \frac{(1 + k)z}{V}\right]\left(\frac{\partial g}{\partial Q}\right). \tag{A.2}$$

$$-\frac{\partial H}{\partial M} = \frac{\partial \lambda_1}{\partial t} \text{ implies}$$

$$\frac{\partial \lambda_1}{\partial t} = -e^{-rt}N[(NB(Y(w)) - C_a(R)) - (NB(Y(x, z(t))) - C_b(E(t), Q(t)))] + \lambda_1 h. \tag{A.3}$$

$$-\frac{\partial H}{\partial N} = \frac{\partial \lambda_2}{\partial t} \text{ implies}$$

$$\frac{\partial \lambda_2}{\partial t} = -e^{-rt}M[(NB(Y(w)) - C_a(R)) - (NB(Y(x, z(t))) - C_b(E(t), Q(t)))] + \lambda_2 m. \tag{A.4}$$

$$-\frac{\partial H}{\partial z} = \frac{\partial \lambda_3}{\partial t} \text{ implies}$$
$$\frac{\partial \lambda_3}{\partial t} = -e^{-rt}\left[\frac{\partial NB(Y(x,z))}{\partial z}\right](1-MN)$$
$$-\lambda_3 g(1-k)\left[1-\frac{2(1+k)z}{V}\right]. \quad \text{(A.5)}$$

$$\frac{\partial H}{\partial \lambda_1} = \frac{\partial M}{\partial t} \text{ implies } \frac{\partial M}{\partial t} = h[1-M]. \quad \text{(A.6)}$$

$$\frac{\partial H}{\partial \lambda_2} = \frac{\partial N}{\partial t} \text{ implies } \frac{\partial N(t)}{\partial t} = m(1-N). \quad \text{(A.7)}$$

$$\frac{\partial H}{\partial \lambda_3} = \frac{\partial z}{\partial t} \text{ implies } \frac{\partial z}{\partial t} = gz(1-k)\left[1-\frac{(1+k)z}{V}\right]. \quad \text{(A.8)}$$

$$\lim_{t\to T}\lambda_1 = 0,\ \lim_{t\to T}\lambda_2 = 0,\ \lim_{t\to T}\lambda_3 = 0,$$
$$\lim_{t\to T}\lambda_1 M \geq 0,\ \lim_{t\to T}\lambda_2 N \geq 0,\ \text{and}\ \lim_{t\to T}\lambda_3 z \geq 0. \quad \text{(A.9)}$$

APPENDIX B—ADJOINT VARIABLES ASSOCIATED WITH INNOVATION, ADOPTION, AND INVASIVE SPECIES STOCK, RESPECTIVELY

$$\lambda_1(t) = \frac{e^{-rt}}{(r+h)}\{[NB(Y(w)) - C_a(R)]$$
$$-[NB(Y(x,z)) - C_b(E,Q)]\} > 0, \quad \text{(B.1)}$$

$$\lambda_2(t) = \frac{e^{-rt}}{(r+m)}\{[NB(Y(w)) - C_a(R)]$$
$$-[NB(Y(x,z)) - C_b(E,Q)]\} > 0, \text{ and} \quad \text{(B.2)}$$

$$\lambda_3(t) = \frac{e^{-rt}(1-MN)}{r-[g(1-k)]\left[1-\frac{2(1+k)z}{V}\right]} \times \left[\frac{\partial NB(Y(x,z))}{\partial z}\right] < 0. \quad \text{(B.3)}$$

APPENDIX C—COMPARATIVE DYNAMICS OF INVASIVE SPECIES CHARACTERISTICS

$$\begin{pmatrix} d\lambda_1 \\ d\lambda_2 \\ d\lambda_3 \end{pmatrix} = D^{-1}\begin{pmatrix} C11 & C12 & C13 \\ C21 & C22 & C23 \\ C31 & C32 & C33 \end{pmatrix}\begin{pmatrix} dg \\ dk \\ dV \end{pmatrix}, \quad \text{(C.1)}$$

where $D = [e^{-(h+m)t}]\{(\frac{\partial m}{\partial Q})(\frac{\partial h}{\partial E}) - (\frac{\partial m}{\partial E})(\frac{\partial h}{\partial Q})\} < 0.$[16]

$$C11 = \lambda_3 e^{-mt}\left\{z\left(1-\frac{2kz}{V}\right)\left(\frac{\partial m}{\partial Q}\right)\left(\frac{\partial k}{\partial E}\right) + \frac{z}{W}(1-k)^2\left(1-\frac{z(1+k)}{V}\right) \times (V-2z(1+k))\left(\frac{\partial g}{\partial Q}\right)\left(\frac{\partial m}{\partial E}\right) + \frac{gz}{W}(1-k)\left(1-\frac{2kz}{V}\right) \times (V-2z(1+k))\left(\frac{\partial m}{\partial Q}\right)\left(\frac{\partial k}{\partial E}\right)\right\} \text{ where}$$
$$W = [(r-g(1-k))V + 2gz(1-k^2)].$$

$$C21 = \lambda_3 e^{-ht}\left\{z(1-\frac{2kz}{V})\left(\frac{\partial h}{\partial Q}\right)\left(\frac{\partial k}{\partial E}\right) + \frac{(1-k)}{W}(V-2z(1+k))\left[gz\left(1-\frac{2kz}{V}\right) \times \left(\frac{\partial h}{\partial Q}\right)\left(\frac{\partial k}{\partial E}\right) - z(1-k)\left(1-\frac{z(1+k)}{V}\right) \times \left(\frac{\partial g}{\partial Q}\right)\left(\frac{\partial h}{\partial E}\right)\right]\right\}.$$

$$C31 = \lambda_3 e^{-(h+m)t}\left\{\frac{(1-k)}{W}(V-2z(1+k))\left[\left(\frac{\partial m}{\partial Q}\right) \times \left(\frac{\partial h}{\partial E}\right) - \left(\frac{\partial h}{\partial Q}\right)\left(\frac{\partial m}{\partial E}\right)\right]\right\}.$$

$$C12 = z\lambda_3 e^{-mt}\left\{\left(-\frac{2gz}{V}\right)\left(\frac{\partial m}{\partial Q}\right)\left(\frac{\partial k}{\partial E}\right) - \left(1-\frac{2kz}{V}\right)\left(\frac{\partial g}{\partial Q}\right)\left(\frac{\partial m}{\partial E}\right)\right.$$

[16]Using Equations (A.1) and (A.2), one can show that $[(\frac{\partial m}{\partial Q})(\frac{\partial h}{\partial E}) - (\frac{\partial m}{\partial E})(\frac{\partial h}{\partial Q})] < 0$.

$$- \frac{g}{W}(V - 4kz)[(1-k)\left(1 - \frac{z(1+k)}{V}\right)\left(\frac{\partial g}{\partial Q}\right) \times \left(\frac{\partial m}{\partial E}\right) + g\left(1 - \frac{2kz}{V}\right)\left(\frac{\partial m}{\partial Q}\right)\left(\frac{\partial k}{\partial E}\right)\Bigg]\Bigg\}.$$

$$C22 = z\lambda_3 e^{-ht}\Bigg\{\left(\frac{2gz}{V}\right)\left(\frac{\partial h}{\partial Q}\right)\left(\frac{\partial k}{\partial E}\right) + \left(1 - \frac{2kz}{V}\right) \times \left(\frac{\partial g}{\partial Q}\right)\left(\frac{\partial h}{\partial E}\right) + \frac{gV}{W}(V - 4kz))\Bigg[(1-k) \times \left(1 - \frac{z(1+k)}{V}\right)\left(\frac{\partial g}{\partial Q}\right)\left(\frac{\partial h}{\partial E}\right) - g\left(1 - \frac{2kz}{V}\right)\left(\frac{\partial h}{\partial Q}\right)\left(\frac{\partial k}{\partial E}\right)\Bigg]\Bigg\}.$$

$$C32 = -\lambda_3 e^{-(h+m)t}\Bigg\{g(V - 4kz)\Bigg[\left(\frac{\partial m}{\partial Q}\right)\left(\frac{\partial h}{\partial E}\right) - \left(\frac{\partial h}{\partial Q}\right)\left(\frac{\partial m}{\partial E}\right)\Bigg]\Bigg\}.$$

$$C13 = z\left(\frac{\lambda_3}{V}\right)e^{-mt}\Bigg\{\left(\frac{2gkz}{V}\right)\left(\frac{\partial m}{\partial Q}\right)\left(\frac{\partial k}{\partial E}\right) + z\left(1 - \frac{(1-k^2)}{V}\right)\left(\frac{\partial g}{\partial Q}\right)\left(\frac{\partial m}{\partial E}\right) + \frac{2gz(1-k^2)}{W}\Bigg[(1-k)\left(1 - \frac{z(1+k)}{V}\right)\left(\frac{\partial g}{\partial Q}\right) \times \left(\frac{\partial m}{\partial E}\right) - g\left(1 - \frac{2kz}{V}\right)\left(\frac{\partial m}{\partial Q}\right)\left(\frac{\partial k}{\partial E}\right)\Bigg]\Bigg\}.$$

$$C23 = z\left(\frac{\lambda_3}{V}\right)e^{-ht}\Bigg\{\left(-\frac{2gkz}{V}\right)\left(\frac{\partial h}{\partial Q}\right)\left(\frac{\partial k}{\partial E}\right) - \frac{z(1-k^2)}{V}\left(\frac{\partial g}{\partial Q}\right)\left(\frac{\partial h}{\partial E}\right) + \frac{2gz(1-k^2)}{W}\Bigg[g\left(1 - \frac{2kz}{V}\right)\left(\frac{\partial h}{\partial Q}\right)\left(\frac{\partial k}{\partial E}\right) - (1-k)\left(1 - \frac{z(1+k)}{V}\right)\left(\frac{\partial g}{\partial Q}\right)\left(\frac{\partial h}{\partial E}\right)\Bigg]\Bigg\}.$$

$$C33 = z\left(\frac{\lambda_3}{V}\right)e^{-(h+m)t}\left(\frac{2g(1-k^2)}{W}\right)\Bigg[\left(\frac{\partial m}{\partial Q}\right)\left(\frac{\partial h}{\partial E}\right) - \left(\frac{\partial h}{\partial Q}\right)\left(\frac{\partial m}{\partial E}\right)\Bigg]\Bigg\}.$$

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